Range of orbital angular momenta available for complete fusion between heavy ions

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RANGE OF ORBITAL ANGULAR MOMENTA AVAILABLE FOR COMPLETE FUSION BETWEEN HEAVY IONS

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Résumé. — Le même noyau composé, ^{158}Er, a été formé par trois différentes voies d'entrée, avec les projectiles ^{16}O, ^{40}Ar et ^{84}Kr. Les fonctions d'excitation des réactions (IL, 5n) et (IL, 6n) sont bien rendues par les calculs statistiques de désexcitation, à la condition de choisir pour les ions Ar et surtout Kr une fenêtre pour les moments angulaires orbitaux susceptibles de provoquer la fusion complète. Curieusement, les ondes partielles de faibles $l\hbar$ doivent être exclues. Ceci implique qu'au cours de l'interaction conduisant à la fusion complète, la dissipation d'énergie par friction tangentielle est importante.

Abstract. — The same compound nucleus, ^{158}Er, has been formed through three different entrance channels, with projectiles ^{16}O, ^{40}Ar and ^{84}Kr. Excitation functions for reactions (HI, 5n) and (HI, 6n) are well fitted by statistical model calculations, provided that a certain window in orbital angular momentum should be taken in order to produce complete fusion in the case of Ar ions and Kr ions. Curiously enough, low l-waves should be avoided. It implies that, during the interaction leading to complete fusion, the energy dissipation by tangential friction should be rather large.

1. **Introduction.** — In a recent paper [1], we have given experimental results on excitation functions of the formation of residual nuclei issued from the same compound nucleus, ^{158}Er, obtained in cross bombardments by different projectiles :

$$\begin{array}{lcl} ^{16}\mathrm{O} + {}^{142}\mathrm{Nd} \searrow & & \nearrow {}^{153}\mathrm{Er} \\ ^{40}\mathrm{Ar} + {}^{118}\mathrm{Sn} \rightarrow & {}^{158}\mathrm{Er}^* & \\ ^{84}\mathrm{Kr} + {}^{74}\mathrm{Ge} \nearrow & & \searrow {}^{152}\mathrm{Er} \end{array}$$

In this letter, we want to show that the de-excitation process can be described with the statistical theory including angular momentum effects, *only if a certain range of orbital angular momenta is selected in the entrance channel for contributing to the compound nucleus cross-section.*

Let us first summarize the main characteristics of the experimental data :

a) Excitation functions (HI, 5n) and (HI, 6n) were found to be much broader for argon projectiles than for lighter ions.

b) When comparing argon and krypton induced reactions, the threshold for the (Kr, xn) excitation function was shifted towards higher excitation energies by more than 15 MeV, although the peak energy was nearly the same, as well as the descent on the high energy side. This is not an effect of the Coulomb barrier since excitation functions for 5n and 6n rise up well above the barrier.

c) Cross-sections for the reactions (Kr, xn) with $x = 4$, 5 and 6, were smaller than for corresponding argon induced reactions. Consequently a lower value of the critical angular momentum was deduced.

2. **Assumption for the introduction of angular momentum into statistical treatment.** — The statistical theory shows that the probability for de-excitation of a compound nucleus of excitation energy E^* and total angular momentum, I, through a particular exit channel is strongly dependent on the level density of the residual nucleus of spin J and energy E^*. The level density for a nuclear system of internal energy E^* and spin J, $\rho(E^*, J)$ is expressed [2] as a function of the state density $\omega(E^*)$ with no spin restriction, and of the mean square projection of angular momentum σ^2 (Gaussian approximation) :

$$\rho(E^*, J) = \frac{\omega(E^*)}{\sqrt{2\,\pi\sigma^2}} \cdot (2\,J + 1) \times \times \left\{ \exp\left(-\frac{J^2}{2\,\sigma^2}\right) - \exp\left(-\frac{(J+1)^2}{2\,\sigma^2}\right) \right\}. \quad (1)$$

For not too large J values, an expansion of the exponentials to the first order gives the well known *approximate* expression :

$$\rho(E^*, J) = \frac{\omega(E^*)}{\sqrt{2\,\pi\sigma^2}} \times \times \frac{(2\,J+1)\,\hbar^2}{2\,\mathfrak{I}t} \exp\left(-\frac{(J+1/2)^2\,\hbar^2}{2\,\mathfrak{I}t}\right) \quad (2)$$

where σ^2 is replaced by $\mathfrak{I}t/\hbar^2$ in the Fermi gas model, and $\mathfrak{I}$ is the moment of inertia and t the nuclear temperature.

Since $\omega(E^*)$ is also usually expressed as a function of $\exp\left(\frac{E^*}{t}\right)$, and since $\frac{(J+1/2)^2\,\hbar^2}{2\,\mathfrak{I}}$ is a rotational energy $E_{\text{rot}}(J)$, then :

$$\rho(E^*, J) = C\frac{(2\,J+1)\,\hbar^2}{2\,\mathfrak{I}t} \times \times E^* \cdot \exp\left\{\frac{E^* - E_{\text{rot}}(J)}{t}\right\} \quad (3)$$

where C is a constant for a given exit channel.

This formulation says that an approximate approach for the description of the effect of J is to assume that the energy dissipated in rotational form is not available for exciting intrinsic states. Therefore, at each step of the de-excitation decay chain, where neutron evaporation competes with other processes like charged particle emission, fission or gamma rays, the relevant excitation energy that should be taken is $E_J^* = (E^* - E_{\text{rot}}(J))$. This is the basic assumption used for computing the probability for the evaporation of x neutrons $P_{xn}(J)$, from an excited nucleus sharing an angular momentum J.

3. **Principle of the method for calculating the neutron emission probability at a bombarding energy $\bar{\text{E}}$ in the center of mass.** — We have first assumed that the J population was given by the orbital angular momentum population $P(l) = 2\,l/l_{\max}^2$ for $l \leqslant l_{\max}$, $P(l) = 0$ for $l > l_{\max}$. If this distribution is divided into m areas of equal probability, the average angular momentum of a given area is defined as $l_K^2 = \frac{1}{2}\,\frac{K}{m}\,l_{\max}^2$ where K is an odd integer between 1 and $2\,m - 1$. Consequently, the average rotational energy is :

$$\bar{E}_{\text{rot}}(K) = \frac{\overline{l_K^2}\,\hbar^2}{2\,\mathfrak{I}} = \frac{K}{2\,m}\,\frac{l_{\max}^2\,\hbar^2}{2\,\mathfrak{I}}$$

where $\mathfrak{I}$ is calculated for a rigid sphere of radius $r_0(A_1 + A_2)^{1/3}$ with $r_0 = 1.225$ fm.

The calculation was made with 10 strips. Instead of taking a single excitation energy $E^* = \bar{E} + Q$, ten excitation energies were defined as

$$E^*(K) = \bar{E} + Q - \bar{E}_{\text{rot}}(K)\,.$$

The probability $P_{xn}(E^*(K))$ for the emission of x neutrons was computed with an evaporation code [1] derived from the Weisskopf [3] statistical model without angular momentum.

For a given bombarding energy $\bar{E}$, the probability for emission of x neutrons was the summation

$$\frac{1}{m}\sum_K P_{xn}(E^*(K))\,.$$

The program has been applied for the three entrance channels (^{16}O + ^{142}Nd), (^{40}Ar + ^{118}Sn) and (^{84}Kr + ^{74}Ge) and for two exit channels (HI, 5n) and (HI, 6n) and the results are given as $P_{xn} = \sigma_{xn}/\sigma_R$ where σ_R is the total reaction cross-section, in order to compare the three systems.

4. **Comparison with excitation functions.** — Figure 1 presents the comparison between the experimental excitation function ^{142}Nd(^{16}O, 5n)^{153}Er and the calculated curve P_{5n}, obtained by considering 10 strips between $l = 0$ and

$$l_{\max}\hbar = (R_1 + R_2)\,[2\,\mu(\bar{E} - V)]^{1/2}$$

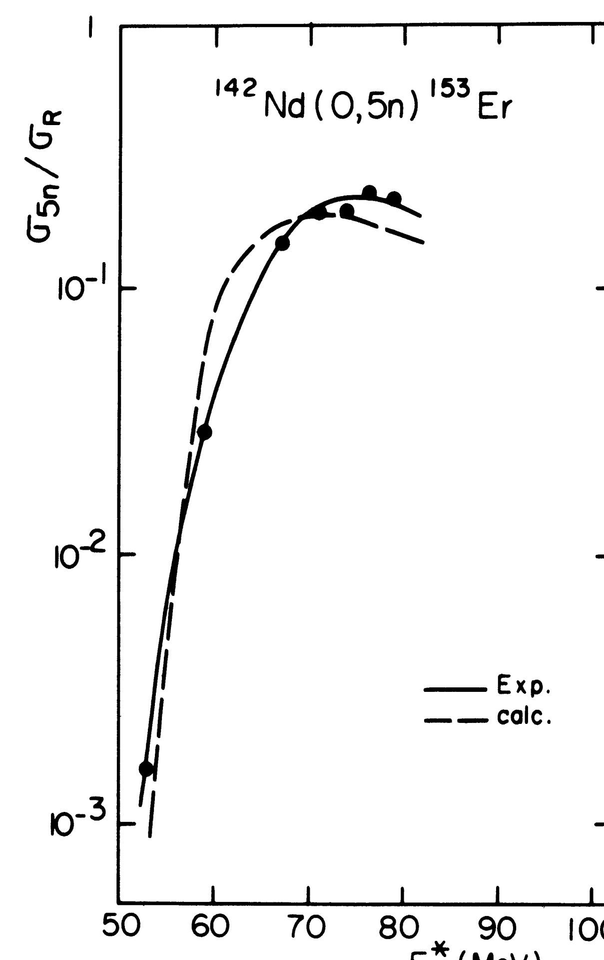

FIG. 1. — Low part of excitation function for the reaction ^{142}Nd(^{16}O, 5n)^{153}Er. Experimental cross sections are represented as crosses and a line has been drawn through these values. The dashed curve has been calculated according to the method described in the text. Excitation energy is related to the laboratory energy by the relation :

$$E^* = \frac{142}{158}\,E_{\text{lab}} - 25\text{ MeV}\,.$$

(1) Blann, M., Private communication.

without any restriction. Since the purpose was to reproduce the rising part of the excitation function, the calculated curve was normalized in absolute scale by fitting the experimental curve at $E^* = 70$ MeV. The threshold of the experimental excitation function was found slightly above the theoretical threshold which should be equal to the sum of the 5 neutron binding energies in ^{158}Er.

In order to fit correctly experimental and calculated curves, we had to shift of about 5 MeV towards higher energies the calculated curves $P(xn) = f(E^*)$ as they were obtained from the evaporation code. Such a small difference is probably not significant because the precision in the threshold energy measurement is certainly not greater than 2 or 3 MeV, and also S_n values extracted from mass tables for very neutron deficient nuclei are probably not quite accurate. For the two other systems which are compared to the (^{16}O + ^{142}Nd) system, the $P(xn)$ functions defined as above have been used.

Figure 2 shows the comparison in the case of ^{118}Sn(Ar, 5n)^{153}Er. The experimental curve is very broad [4]. However, when all l values are included in the calculation the $P(5n)$ curve decreases very slowly on the high energy side and a large discrepancy appears above 95 MeV. In order to reproduce the descent of the excitation function, the angular momentum distribution has to be cut down at a critical value for evaporation residue formation, which depends on the excitation energy. Such a l_{cr}(max) has been determined in order to obtain the best fit, for $x = 5$ and $x = 6$.

Another discrepancy appears on the low energy side since the rising part of the experimental cross-section is found at 5 MeV above the calculated (P, 5n) curve as it was fitted with (^{16}O, 5n). That part corresponds to the fraction of compound nuclei with low angular momenta, since all the available energy should be used for the evaporation of 5 neutrons and the part left for rotational energy should be as small as possible in $E^*(K) = \bar{E} + Q - E_{rot}(K)$. Then we made the unexpected assumption [1-5] that low l-waves do not contribute to the compound nucleus formation, and that a lower cut-off may exist in the l population for complete fusion. As it is shown on figure 2, a good agreement is observed with l_{cr}(min) around 25 $\hbar$. Above 75 MeV, the probability for the reaction (Ar, 5n) without angular momentum becomes very small and there cannot be any significant contribution of the low part of the angular momentum population to the excitation function. The exact position of the rising part of the (P, 5n) calculated curve is very sensitive to the l_{cr}(min) value. Therefore the experimental uncertainty in the energy measurements inhibits the determination of a precise l_{cr}(min), if it exists. Figure 3, referring to (Kr, 5n) reaction, shows a much more pronounced effect since there is a shift of more than 15 MeV in excitation energy between the calculated and the experimental thresholds, that corresponds to about 30 MeV in bombarding energy. Note also that the rising part of the calculated curve

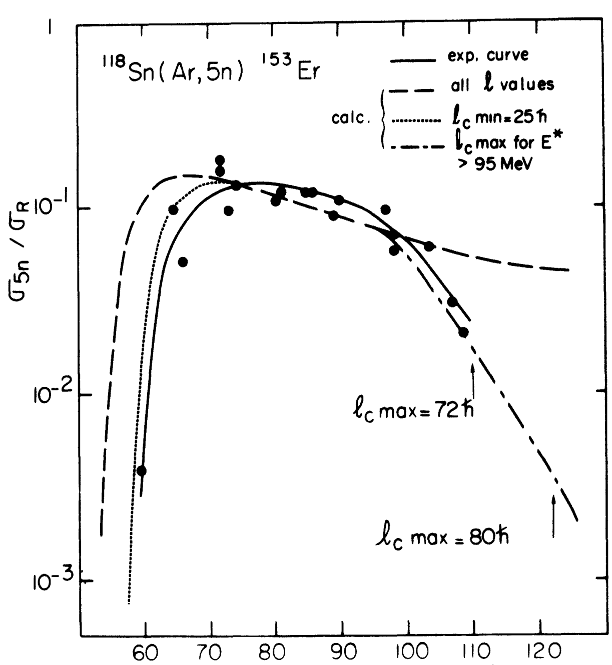

FIG. 2. — Excitation function for the reaction ^{118}Sn(Ar, 5n)^{153}Er. A continuous line is drawn through experimental points. For energies lower than 70 MeV calculations with a critical l_c min = 25 $\hbar$ give the best fit. For energies higher than 95 MeV, an upper limit, l_c max is necessary :

$$E^* = \frac{118}{158} E_{lab} - 61 \text{ MeV}.$$

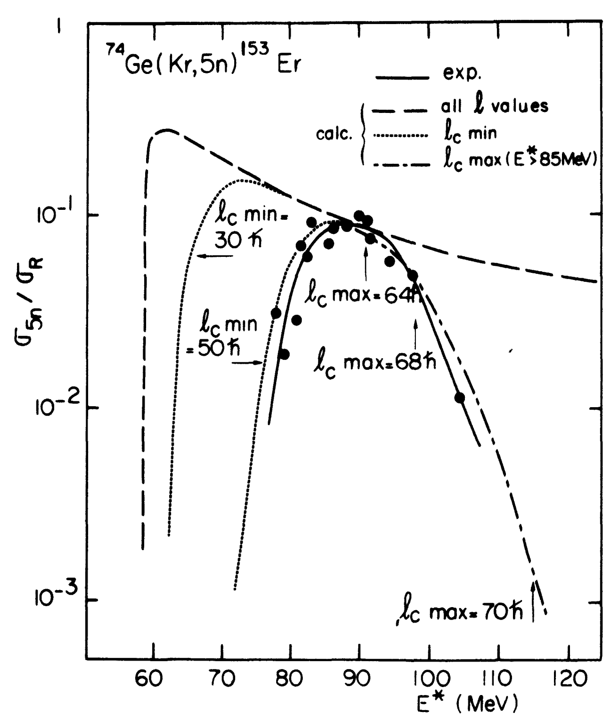

FIG. 3. — Excitation function for the reaction ^{74}Ge(^{84}Kr, 5n)^{153}Er. Same caption as in figure 2. Attempts for different l_c values are shown on the low side and high side :

$$E^* = \frac{74}{158} E_{lab} - 91 \text{ MeV}.$$

with no l_{cr}(min) is abnormally sharp, because there is a cut-off effect due to the Coulomb barrier at 60 MeV [1]. In order to reproduce the experimental excitation function, the best fit is obtained with a lower limit, l_{cr}(min) $\hbar$, around 50 $\hbar$ and also, for the high energy descent, with a higher limit varying between 64 and 70 $\hbar$, depending on the energy.

Such a narrow window in the angular momentum population explains both the lower cross-section and the width of the excitation function. The precise value of the lower cut-off should not be taken as a definitive determination. First of all, the step function is probably a rough approximation. Second, the calculation goes through a decomposition of l population in ten strips which is perhaps not sufficient. Even more serious is the use of an approximate expression for the level density (subtraction of the rotational energy) and the choice of a rigid body moment of inertia. A lower $\mathfrak{J}$ value would lead to a lower value for l_{cr}(min). Our goal here, was only to stress qualitatively the necessity of a cut-off on the low side of the angular momentum population. We are presently trying to improve the quantitative aspect of this observation by using the code Alice [6].

For heavier target nuclei, an even narrower l window should be available for complete fusion and therefore the very low cross-section of fusion observed [7] in the case of (^{84}Kr + ^{209}Bi) seems consistent with the results obtained on (^{84}Kr + ^{74}Ge).

The hypothesis of limiting the complete fusion on the low l wave side, i.e., for head-on collisions, might appear surprising at the first glance, and is certainly not correct for light ions.

For low l waves, the energy is dissipated during the interaction only along a radial friction effect. Furthermore, when the coulomb potential is dominant (high $Z_1 Z_2$ product), the penetration of the two colliding partners might not be complete enough to lead to a spherical shape. In this case, the consequence would then be the quasi-fission phenomenon [7-8].

For higher l waves, large losses of orbital angular momenta could occur during the collision helping energy dissipation. The effect is one of tangential friction leading to a rotating compound nucleus. Tsang [9] has given a theoretical basis to these qualitative considerations, and the results described above seem for the moment to furnish rather convincing arguments in favor of the great importance of tangential friction.

Bondorf *et al.* [10], in their friction model, for heavy ion interactions, come to the conclusion that deep inelastic collisions or quasi-fissions could occur in a range of l waves included between two regions of l, one above and one below, where complete fusion takes place. Our result suggests that, if one follows their model, the low l zone should correspond in our case to a negligeable cross-section and the main part of complete fusion corresponds to the high l zone. Very recently, Wilczyinski [11] has also predicted the absence of complete fusion for small impact parameters mainly due to deformation effects.

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